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MARCH, 1920

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Vol. IV MARCH, 1920 Number 2

THE RESPONSE OF THE AVERAGE PUPIL TO VARIOUS INTENSITIES OF LIGHT.

BY

PRENTICE REEVES.

THE eye is probably the most remarkable product of Nature's process of evolution. It is a sensory and a motor organ as we receive impressions from the world about us through the stimulation of the retina and also from the functioning of the eye muscles. As a sensory organ the eye ranks first, and even with the average imperfections it remains very efficient. As a motor organ the eye is capable of extremely fine discriminations. In addition to these facts the eye may be considered as a physical instrument. The eye and the photographic plate are the most widely used physical instruments in dealing with problems in light and in the majority of such problems the final decisions are rendered by the eye. It has been shown that the eye functions efficiently over a much wider range than any other known instrument, and, furthermore, it possesses the property of continually renewing its sensitiveness, except in the extreme upper limits of stimulation. Although we know quite a little about the dioptrics of the eye, we are as yet uninformed as to the exact nature of the retinal image and the physiological or psychological factors in visual perception. While we can not measure visual perceptions directly, we can accurately control the physical stimuli and determine the reaction of the retina to various intensities of illumination such as have been expressed as threshold sensibility, contrast sensibility, and glare sensibility. These sensibilities vary with several factors,

the principal one of which is the brightness under which the eye is working.

For each brightness level used the pupil has a different diameter, as the pupil is automatically adjusted so as to tend to maintain constant light energy on the retina. That is, when the intensity of illumination is increased the pupil contracts and *vice versa*, or if the distance between the eye and stimulus is changed, the pupil is also changed to keep the retinal illumination constant. The literature on this subject of pupillary reactions deals largely with pathological cases and the results from normal eyes are few and show a lack of agreement.[1] In this study all subjects were normal and the data are offered as such.[2]

The procedure used by Blanchard[3] on the consensual reflex, *i.e.*, the effect of exposing one or both eyes to the light, was repeated, and although the actual pupillary diameters are different, the shape of the various curves is the same as Blanchard's. In this part of the experiment the subject's eye was focused on the ground glass of a 5 x 7 view camera and his head fixed in a head rest. A small millimetre scale was placed in the plane of the pupil so it would be magnified to the same extent as the pupil and simplify the reading of the records. After fifteen minutes' adaptation to total darkness a flashlight photograph was taken. The procedure was repeated for several brightness levels ranging from total darkness to a just tolerable reflection of direct sunlight from white drawing paper. The effect of exposing one or both eyes was studied throughout the entire range of brightness. Fig. 1 and Table I show the results obtained from one of the subjects, and it will be seen that in the range of ordinary intensities there is a marked effect of closing one eye.

From these results it is seen that the amount of contraction of the pupil for brightnesses in excess of 100 millilamberts is slight, so the photographs of six other subjects were taken for six brightness levels chosen from the curve just shown. In this way the minimum diameter obtained is near the actual minimum and the subjects were not exposed to the very unpleasant glare.

---

[1] Blakesley, *Phil. Mag.*, 1910, **29**, 960; Nutting, *Trans. Ill. Eng. Soc.*, 1916, **11**, 1; Reeves, *Astrophys. J.*, 1917, **46**, 167; Langfeld, *Zsch. f. Sinnesphysiol.*, 1908, **42**, 349; Stevenson, *J. of Brit. Astron. Assn.*, 1916, **26**, 303.

[2] Similar treatment of data in *Psychol. Rev.*, 1918, **25**, 330.

[3] *Phys. Rev.*, 1918, **11**, 81.

In this part of the experiment a motion picture camera was used with an extension for "close ups" so that a full-sized image of the pupil could be recorded. A bank of lamps was used instead of the flash powder. Several pictures were taken of each subject

FIG. 1.

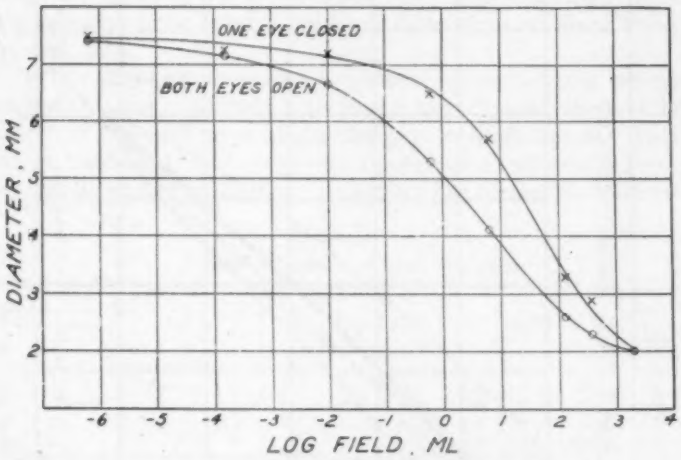


TABLE I.

Effect of Closing One Eye on Pupillary Diameters.

Brightness in millilamberts	Log B	Both eyes exposed		One eye closed		Difference	
		J. B.	*P. R.*	*J. B.*	*P. R.*	*J. B.*	*P. R.*
0	Taken as −6.0	7.4	8.6	7.5	8.6	0.1	0
0.00015	−3.82	7.1	8.5	7.2	8.5	0.1	0
0.01	−2.0	6.7	8.3	7.2	8.5	0.5	0.2
0.6	−0.22	5.3	7.0	6.5	7.8	1.2	0.8
6.3	0.8	4.1	4.3	5.7	5.9	1.6	1.6
126.0	2.1	2.6	2.9	3.3	3.3	0.7	0.4
355.	2.55	2.3	2.4	2.9	2.9	0.6	0.5
2000.	3.3	2.0	1.9	2.0	2.0	0	0.1

on different days and the results averaged. Fig. 2 and Table II show the results from the six subjects and we see individual differences in the separate curves with marked variations in the maximum diameters. The average eye is represented by the heavy line and from this curve we are able to determine the

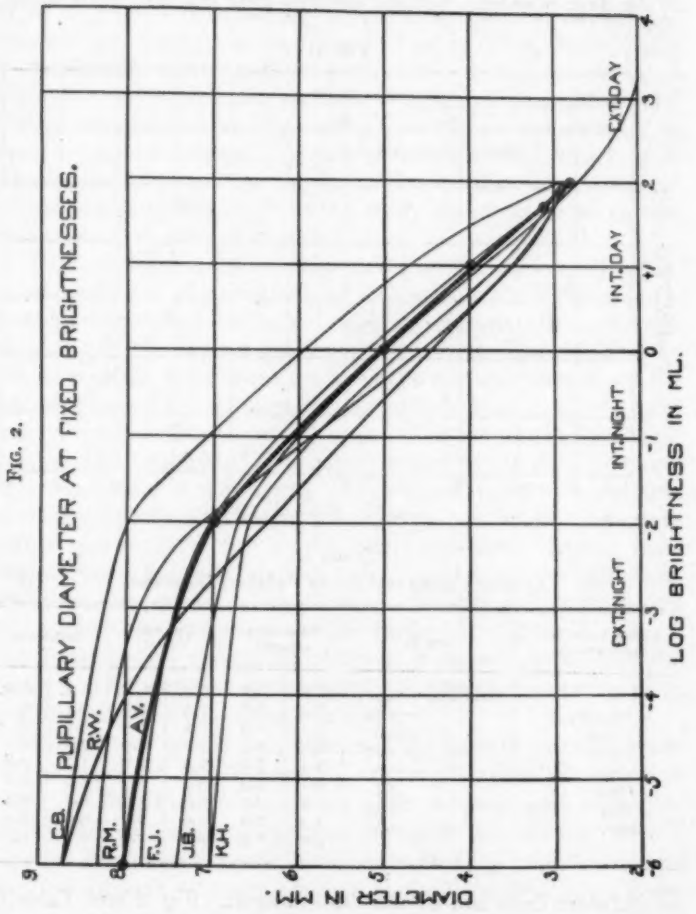

PUPILLARY DIAMETER AT FIXED BRIGHTNESSES.
C.B.
R.W.
R.M.
A.V.
F.J.
J.B.
K.H.
DIAMETER IN MM.
LOG BRIGHTNESS IN ML.
EXTNGHT
INTNGHT
INTDAY
EXTDAY

FIG. 2.

dimensions of an average pupil for any given brightness. In ordinary practice we seldom use either the maximum or minimum diameters which may be taken as 8 mm. and 2 mm., but ordinarily take the range from 2.5 to 7 mm. It might be well to add at this point that the diameters we measure in these photographs are really the apparent diameters when viewed through the cornea and aqueous humor and that the actual dimensions are about seven per cent. less.

When changing from one brightness to another the retinal sensibility changes and has been shown to occupy an appreciable period of time for even slight changes in illumination. This change consists of two factors—a retinal process (whatever it may be) and the change in pupillary diameter. The former is explained

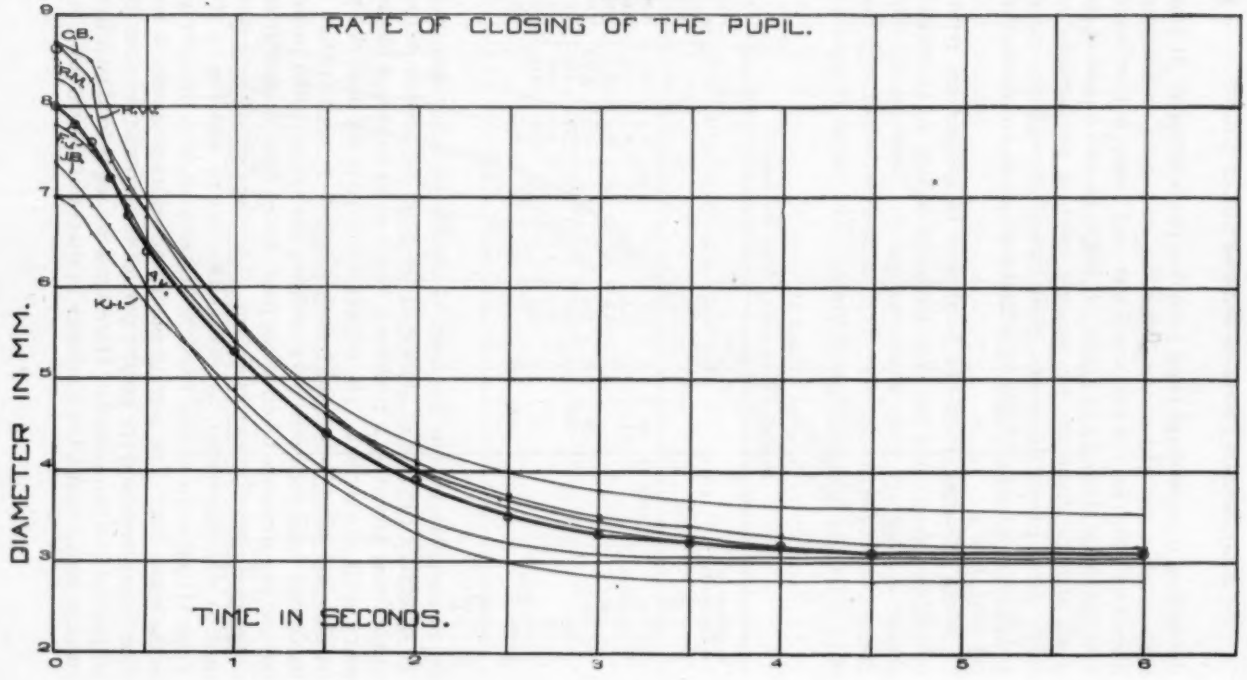
TABLE II.

Pupillary Diameters at Fixed Brightnesses.

Brightness in millilamberts	Log B	J.B.	C.B.	K.H.	F.J.	R.M.	R.W.	Average of 6 subjects
0	Taken as −6	7.4	8.7	7.0	7.8	8.3	8.7	8.0
0.00015	−3.8	7.1	8.4	6.8	7.6	8.1	7.9	7.6
.01	−2	6.7	8.0	6.7	7.0	7.1	6.3	7.0
1.0	0	5.0	5.9	4.8	5.2	4.6	4.5	5.0
10.	1.0	3.9	4.8	3.6	4.6	3.5	3.5	4.0
55.	1.7	3.0	3.5	3.1	3.1	3.0	2.9	3.1
100.	2	2.7	2.9	2.7	2.9	2.8	2.9	2.8
2000.	3.3	2.0	....	....	....	....	....	2.0

by various theories but the latter is capable of being measured. To determine the rate of closing of the pupil the motion picture camera was driven by a controlled motor so as to take a picture every tenth of a second. The subject was fixed in the head rest as before, and after being fully dark adapted so as to obtain a maximum pupil the camera was started, the taking lights turned on, and pictures were taken as the pupil closed from its maximum to the minimum diameter as chosen. The same six subjects were used in this experiment, as well as two others, and Fig. 3 and Table III show the results from the six subjects with the average in the heavy line. The average pupil reached its minimum in less than five seconds and the greater part of the contraction occurred within the first two seconds. Here again we see individual differences in actual values but similarity in shapes of the curves.

FIG. 3.


RATE OF CLOSING OF THE PUPIL.
C.B.
R.M.
K.H.
DIAMETER IN MM.
TIME IN SECONDS.
9
8
7
6
5
4
3
2
0
1
2
3
4
5
6

In order to get data on the rate of opening of the pupil it was necessary to make a rather elaborate electrical device which would turn off the lights for any given time, to allow the pupil to dilate, then start the motion picture camera and turn on the taking lights in time to photograph the pupil after the required time in darkness. A preliminary series was run on one subject in order to obtain the proper time intervals for opening and eleven intervals were chosen, ranging from one-half second to five minutes. The same six subjects were photographed and Fig. 4 and Table IV show the results obtained. The opening of the pupil to a maximum

TABLE III.

Rate of Closing of the Pupil.

Number of picture	Time in seconds	J. B.	C. B.	K. H.	F. J.	R. M.	R. W.	Average of 6 subjects
1	0	7.4	8.7	7.0	7.8	8.3	8.7	8.0
2	.1	7.2	8.6	6.9	7.7	8.2	8.5	7.8
3	.2	6.9	8.5	6.6	7.5	7.9	8.3	7.6
4	.3	6.7	8.0	6.4	7.2	7.5	7.4	7.2
5	.4	6.3	7.5	6.1	6.9	7.2	7.1	6.8
6	.5	6.0	7.0	5.8	6.0	6.9	6.8	6.4
11	1.0	4.7	5.7	4.9	5.4	5.4	5.8	5.3
16	1.5	3.9	4.8	4.0	4.6	4.6	4.7	4.4
21	2.0	3.3	4.3	3.6	4.1	4.0	4.0	3.9
26	2.5	3.0	4.0	3.2	3.7	3.7	3.7	3.5
31	3.0	2.9	3.8	3.1	3.5	3.3	3.5	3.3
36	3.5	2.8	3.6	3.0	3.4	3.3	3.2	3.2
41	4.0	2.8	3.7	3.1	3.3	3.1	3.2	3.2
46	4.5	2.8	3.7	3.0	3.2	3.1	3.1	3.1
51	5.0	2.8	....	....	....	....	3.1	....
	1 minute	2.8	3.4	3.1	3.1	3.1	3.1	3.1

diameter requires as many minutes as it required seconds for it to close to the minimum. (The explanation of this difference would probably involve quite a philosophical discourse.)

As the pupil varies with changes in convergence, this factor was kept constant by having a constant fixation point 35 cm. directly in front of the subject. When working in the fainter intensities and darkness an illuminated pinhole was used, and it was kept at a just perceptible brightness for a few seconds before the photograph was to be taken, by the subject himself. The data plotted in all curves represent the average of at least four series on different days from each subject and as high as twenty series from some. The daily variation, however, was

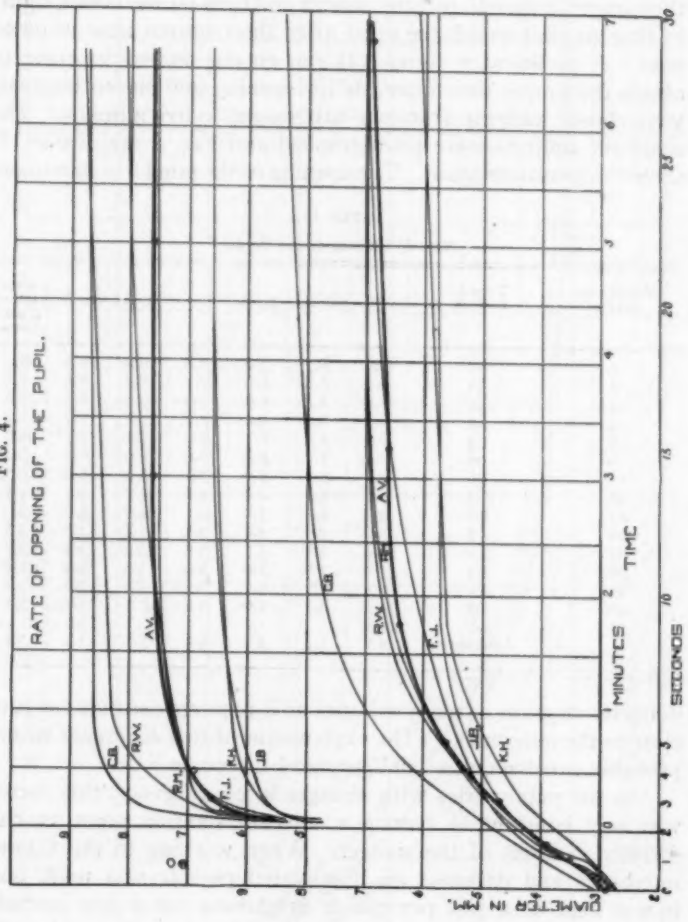

RATE OF OPENING OF THE PUPIL.
DIAMETER IN MM.
TIME
MINUTES
SECONDS
AV.
RVV.
F.J.
KH.
JB.

FIG. 4.

slight. Age has been found to be a factor in pupillary reflex,[4] but none of the subjects were old enough to expect any age effects.

When considering the results on the opening and closing of the pupil, it must be remembered that these data were obtained from changing from one definite brightness to another, darkness and 100 millilamberts. We could expect different results if we used any other brightness range. The light sources used in the entire experiment were sunlight and tungsten filament lamps, so that we might expect other values if colored (especially monochromatic) light were used.

TABLE IV.
Rate of Opening of the Pupil.

Time in darkness	J. B.	C. B.	K. H.	F. J.	R. M.	R. W.	Average of 6 subjects
0	2.7	3.1	2.7	2.9	2.8	3.0	2.9
.5 seconds	3.0	3.5	2.9	3.1	3.0	3.2	3.1
1.0 seconds	3.2	4.0	3.2	3.6	3.6	3.7	3.5
1.5 seconds	3.9	4.4	3.4	4.2	3.9	3.8	3.9
3.0 seconds	4.7	5.3	4.3	4.7	5.0	4.4	4.7
5.0 seconds	5.3	6.6	4.9	5.4	5.8	5.7	5.6
9. seconds	5.7	7.6	5.6	6.0	6.6	6.7	6.4
15. seconds	5.7	8.0	5.5	6.6	6.9	6.9	6.6
29. seconds	5.8	8.4	6.1	7.0	7.0	7.0	6.9
1 minute	6.2	8.6	6.3	7.3	7.2	8.3	7.3
3 minutes	6.6	8.7	6.5	7.5	7.8	8.5	7.6
5 minutes	6.6	8.6	6.6	7.3	8.0	8.7	7.6
10 minutes	....	8.9	....	....	....	....	....

In experiments where it is essential to know the light energy striking the retina, the diameter of the pupil is an important item. In choosing artificial pupils we should know at least the minimal working pupil. The designer of optical instruments is very directly interested in pupillary dimensions. The ophthalmologist often determines the diameter of the patient's pupils and examines the pupillary reflexes. In many pathological cases one of the earliest symptoms to appear is a change in the pupillary reflex.

This study has merely touched a very interesting field and valuable information will be found in the treatment of other combinations of brightnesses and also in the use of colored light.

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EASTMAN KODAK CO.,
ROCHESTER, N. Y.

[4] Kanngieser, F., *Arch. f. Augenhk.*, 1909, 63, 78; Langfeld, *op. cit.*

A NEW SOFT FOCUS SCREEN FOR PORTRAIT PHOTOGRAPHY.

BY

C. W. FREDERICK.

In portrait work it is not always desirable that a lens should give sharp definition because marks and blemishes are brought out too clearly. Lines and similar defects must be smoothed out to resemble more nearly what the casual eye sees under ordinary white light. This is usually done by retouching the negative, or by employing a lens with soft definition, or both. Soft definition may be obtained in many ways, but its character makes a great difference in the appearance of a picture. It may be produced by merely throwing the lens out of focus, but the effect is not pleasing because the definition is obliterated too completely. We want something that will leave the main features of the picture clearly sketched and at the same time smooth out or obliterate unimportant or disfiguring details.

The usual method of producing soft definition is to modify the design of the lens so that it will fall off in spherical aberration. Thus the image formed by light passing through an outer zone of the lens will not be at the same distance as that formed by light passing through the central portion of the lens, and intermediate images will be formed at intermediate points, so within a certain range a part of the light will form a sharp image and the remainder a series of superposed fuzzy images. The effect aimed at is definition with a mellow outline.

It may be readily understood that the character of the effect will depend upon the distribution of light in the sharp and the fuzzy images, which distribution may be influenced by lens type and different adjustments as to spherical aberration. But the nature of spherical aberration places certain limitations upon the problem. We can not, for example, adjust the aberration of a lens so that three-fourths of the light will form a sharp image and the remaining one-fourth a diffuse image; thus we are cut off from many effects that may be desirable. It usually happens that there is too much light in the diffuse images, so that double lines appear in certain portions of the picture where there is a great

change from white to black, as a white collar against a black coat, or a well-lighted cheek against a dark background.

The natural distribution of light due to spherical aberration may be modified by interposing an opaque diaphragm with a small central opening to allow the sharp image to be formed and radial openings to control the amount of light in the diffuse image. But such a device has the disadvantage of slowing down the lens to an inconvenient degree. However, it was a study of the action of such a diaphragm that suggested the new diffusing screen which is the subject of this paper.

The necessity for a means of diffusion independent of the lens arose in connection with a new enlarging camera which was being developed. This camera was fitted with a device which kept the lens automatically in focus as the enlargement was varied. It was to be used in enlarging portraits, and it was necessary that both sharp definition and soft definition could be obtained at will. It would have been an easy matter to design a mount for the lens which by unscrewing one component would alter the relative positions of the lens elements and introduce spherical aberration. But this would cause a change in the focal length of the lens, and any change in this would prevent its proper functioning. Thus it was necessary to find something independent of the lens.

What at first appeared to be a hardship led eventually to emancipation. Many things were thought of and tried. Diffraction was invoked and rejected. Semitransparent material such as cloth and ground glass were tried but found to slow down the lens too much. Glass slides, coated with transparent varnish giving an undulatory surface, failed to prove satisfactory because the diffusion was not controlled, some of the light being scattered so far that the entire picture was flattened.

We were finally led to try glass discs with fine grooves polished in them. If the grooves were accurately cut the diffusion would be controlled so that no ray of light could deviate more than a limited angle, a few minutes, from its undisturbed path, and thus the picture would not be flattened by stray light. Of course the smoothing out of fine detail will give a certain appearance of flattening which can not be avoided, but this is not noticeable in portrait photography. The discs were placed directly in front of the lens, and being entirely transparent caused no slowing down of the combination.

A great many experiments were tried with different devices for cutting the grooves, different depths and widths of grooves, and different patterns cut upon the disc. The possibilities were endless, and each change had an individuality of its own in its effect upon a photograph.

First we tried concentric circular grooves cut upon the outer portion of the glass disc, leaving the central portion clear for about half the aperture of the lens. The light passing through the central portion of the screen would give a sharp definition, and that passing through the outer portion of the screen diffuse definition. Then by merely stopping the lens the amount of light in the diffuse image could be reduced, and the relative proportion of light in the sharp and diffuse images altered at will. But this screen proved unsatisfactory because it was found to give double lines along boundaries of strong contrast, there being too much light in the rays of maximum deviation. Also the circular grooves were hard to cut.

To get around these difficulties we changed to cylindrical grooves ground in intersecting linear patterns. It was expected the intersecting grooves would diminish the area of maximum slopes, and thus reduce the amount of light of maximum diffusion. But this, too, was a failure, as it was found the successive systems of grooves simply superposed themselves upon the glass surface whether flat or undulating. At the intersection of two grooves the glass was abraded to twice the depth for one groove, and no advantage was obtained.

The grooves could be readily examined by means of interference fringes. When the ground surface of one disc was placed in contact with the unground surface of another, interference bands would appear, giving a very beautiful contour map of the whole system of cuts. When seen under a mercury lamp these contour lines became very sharp indeed, making it easily possible to estimate the depth of the cuts to one or to two millionths of an inch.

Finally, after many experiments, a screen was settled upon in which there were three systems of linear grooves ground at angles of one hundred and twenty degrees from each other, and the grooves of each system were spaced at equal intervals apart but were progressively of increasing depth from the centre outward. The finished pattern showed hexagonal areas of clear glass

constituting about two-thirds of the area of the entire screen. Thus two-thirds of the light was allowed to form a sharp image, and the remaining one-third a succession of soft images varying in diffuseness according to the depth of the successive grooves of the screen. The screen gives soft effects without a trace of double lines, and at the same time it gives definition that does not fail under a magnifier. Its effect may be slightly modified by stopping down the lens.

The results obtained with this screen were very good indeed and distinctly better than anything that could be done with a soft focus lens. In fact, they were so promising that we hastened to apply for a patent upon the idea.*

The screens are capable of many unusual effects. One screen was ground with a single system of parallel grooves, which when used with the diffusion vertical in a portrait had a tendency to make the face appear longer, or if the diffusion were horizontal the face would appear broader. In landscapes it gave similar effects. If the diffusion were vertical the corresponding detail, such as grass or tree trunks, would remain sharp in the picture, while horizontal detail as limbs and twigs of trees would be fuzzed out. Thus it is possible that with proper care effects could be obtained similar to those seen in the paintings of Corot.

A rectangular system of grooves gives a very satisfactory screen for landscapes, and also for portraits. If placed with the diffusion at about forty-five degrees the detail of a landscape will be streaked out in a way suggestive of etching. It is possible that a rectangular system with one set of grooves deeper than the other would be found useful.

One screen of the hexagonal type was ground with one system of grooves strong and the other two weak, but we have not had time to give it a serious test. It might be used to alter the length of a face, or might be turned so as to bring out better detail in hair, or to alter the appearance of cloth in a dress or coat. A satin dress should preserve its peculiar sheen much better if the greater diffusion were directed parallel to the grain of the cloth.

A fundamental peculiarity of all the screens consisting of

* [EDITOR'S NOTE: Unfortunately, no known printing process can reproduce the striking and beautiful effects shown by the pictures submitted by Mr. Frederick in illustration of the work done by means of this new diffusing screen. These include a landscape and a dozen or more large portraits.]

systems of straight lines is that the diffusion occurs at right angles to the various systems, and does not occur equally in all directions. If a small hole be pricked in a negative its image in the enlargement will be seen to consist of a point with short radial streamers extending out from it in a star-like pattern. This is probably beneficial in helping to preserve the contrast between the blacks and whites in fine detail, as one set of streamers is likely to coincide closely with the direction of the detail, thus adding to the already preponderant light in the sharp image, while subtracting nothing from the softening effect upon the picture.

While most of our efforts have been directed toward developing a diffusing screen for enlarging cameras, it is possible that they may be useful also in direct portrait photography. A few large screens for this purpose were ground at haphazard, and tried in a tentative way. The results seemed to indicate that the problem of direct taking was somewhat different from that of enlarging, and would require a different type of screen. In direct taking the screen causes the white areas to encroach upon the black, producing an effect similar to halation, while in the case of enlarging, the black areas encroach upon the white and do not produce the effect of halation. Thus in direct photography a white collar will irradiate upon a black coat and spoil the appearance of the picture, while in an enlargement the black coat will encroach upon the white collar with no unpleasant effect. However, by limiting the diffusion and modifying its distribution it is quite likely that a satisfactory screen may be developed for direct photography. At least the action of the screen in this case is similar to that of the soft focus lenses now in use, and the greater adaptability of the screen should be in its favor.

HAWK EYE WORKS, EASTMAN KODAK COMPANY,
ROCHESTER, N. Y., Feb., 1920.

THE IONIZATION AND RESONANCE POTENTIALS OF NITROGEN, OXYGEN AND HYDROGEN.*

BY

F. L. MOHLER and PAUL D. FOOTE.

THE methods [1] used by the authors in the measurement of critical potentials for electron currents in metallic and non-metallic vapors have been applied, with some modifications, to a study of several gases. A four-electrode tube was employed containing a hot-wire cathode surrounded by two cylindrical grids and a plate. One grid was mounted close to the cathode and the other close to the plate, with a relatively large distance between grids. The electrodes were of platinum sheet and gauze. The tube was connected to pumps and to a gas reservoir so that the gas could be either streamed through the tube or maintained stagnant.

Of the several possible methods for applying potential and for measuring current, the following was found the most satisfactory. A variable accelerating field was applied between the cathode and inner grid; the two grids were maintained at the same potential; a retarding field was fixed between the outer grid and plate; and the current reaching the plate was observed. Thus, if the cathode were at zero potential, the grids were at $+V_1$ and the plate at $V_1 - V_2$.

When V_2 is small, measurement of the electron current reaching the plate furnishes a sensitive indication of potentials of inelastic impact. If V_2 is greater than V_1, so that electrons from the cathode are unable to reach the plate, positive current flows to the plate, above the ionization potential. This is the Lenard method for detecting ionization. Davis and Goucher [2] have shown that the radiation emitted at the resonance potential produces a photo-

* Abstract.

[1] Tate and Foote, *Phil. Mag.*, **36**, p 64, 1918; Bur. Stds. S 317; Foote and Mohler, *Phil. Mag.*, **37**, p 33, 1919; *J. Wash. Acad. Sci.*, **8**, p 513, 1918; Foote, Rognley and Mohler, *Phys. R.*, **13**, p 59, 1919; Mohler, Foote and Stimson, Bur. Std. S 368; Mohler and Foote, Abstract of Non-metallic Vapors, *Phys. R.* (in press).

[2] Davis and Goucher, *Phys. R.*, **10**, p 101, 1917.

electric emission from the plate, giving rise to a current easily mistaken for ionization. As these investigators have demonstrated, it is possible to so connect a four-electrode tube as to differentiate these two effects. We have found that while the ionization effect was of the same magnitude as the partial electron current when V_2 was small, the radiation effect was very much less.

The usual procedure, as in the earlier work, was to determine the resonance potential from the applied potentials at successive inflections in the curve, plate current *versus* accelerating field, and to add to the observed potential, at ionization, the value of the initial potential determined from the partial current curve.

NITROGEN.

The work of Franck and Hertz gave 7.5 volts for the ionization potential but Davis and Goucher[3] showed that radiation without ionization was emitted at 7.5 volts and that the true ionization potential was about 18 volts. Smyth,[4] using a three-electrode tube and the Lenard method, observed the resonance potential as 8.29 volts and confirmed Davis and Goucher's value for ionization.

In our work, commercial nitrogen purified by hot copper, calcium chloride, and liquid air traps was employed. Plate currents with V_2 small showed as many as three sharp inflections due to successive resonance collisions. By the Lenard method the ionization point as well as the radiation effect at the resonance potential were readily detected. Ionization was measured by three methods:

1. Measuring the potential at which the total electron current increased sharply and correcting for initial potential determined from a partial current curve showing resonance points.

2. Measuring by the Lenard method, using the same galvanometer sensitivity as with partial current curves and correcting as before.

3. Measuring by the Lenard method, with high sensitivity, the potential difference between the occurrence of the radiation and ionization effects.

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[3] Davis and Goucher, *Phys. R.*, 13, p 1, 1919.

[4] Smyth, *Phys. R.*, 14, p 409, 1919.

The three methods were in close agreement, giving the final mean as follows:

Resonance potential = 8.18 ± 0.1 volts.
Ionization potential = 16.9 ± 0.5 volts.

Smyth's conclusion that the principal resonance potential corresponds, by the quantum relation, to the nitrogen doublet, observed by Lyman $\lambda = 1492.8$ A and $\lambda = 1494.8$ A is confirmed by our work. The theoretical value is $V = 8.26$ volts in excellent agreement with our observed value of 8.18 volts. Accordingly it appears likely that this line is the first term of a series converging at $\lambda = 730$ A (equivalent to 16.9 volts).

OXYGEN.

Other observers using the Lenard method have obtained results for the ionization potential of oxygen as follows:

Franck and Hertz	9 volts
Mayer	9.5 volts
Hughes and Dixon	9.2 volts
Bishop	9 volts

However, it is to be suspected that the above values are for the resonance potential and that the ionization potential is considerably higher.

Oxygen was made electrolytically and dried as in the work with nitrogen. Plate currents showed the inflections due to successive resonance collisions very distinctly, as many as four reversals of nearly equal sharpness being readily obtained. Ionization was measured by the Lenard method with the correction for initial potential determined from the partial current curves. The radiation method did not give results of much value, suggesting that platinum in oxygen may be less photo-sensitive than in nitrogen.

The following final results were obtained for oxygen:

Resonance potential = 7.91 ± 0.1 volts
Ionization potential = 15.5 ± 0.5 volts

These values indicate that $\lambda = 1570$A is the single line spectrum of nitrogen and the first member of a series converging at $\lambda = 800$ A.

HYDROGEN.

Since the development of the Bohr theory the study of hydrogen is of especial interest. From this theory it would follow that the ionization potential for a hydrogen atom should be determined by the limit of the Lyman series, *i.e.*, the Rydberg number, giving $V = 13.5$ volts and that the resonance potential should be three-fourths of this value, corresponding to an electron displacement from the first to the second orbit. The theory for the normal hydrogen molecule is not so definite. It seems quite likely, however, that the ionization potential for the molecule should be greater than that for the atom by an amount equivalent to the work required to dissociate a molecule. Thus the simplest ionization of a molecule would result in a neutral atom and an ionized atom.

The work of numerous investigators has led to the value 11 volts for ionization, thereby raising a very serious difficulty in the acceptance of Bohr's theory. In addition to the ionization at 11 volts, Davis and Goucher observed ionization at 15.8 volts and inelastic collision *without* ionization at 13.6 volts.

Since our work described below was completed, a paper by Horton and Davies [5] has appeared in which they have arrived at conclusions very similar to ours, and it now seems certain that Bohr's theory of atomic hydrogen satisfactorily interprets the results. Less conclusive is the evidence for molecular hydrogen, since the heat of dissociation amounts to but 2.7 volts on Bohr's theory and to 3.9 volts as experimentally observed by Langmuir,[6] the latter value being frequently cited as an objection to Bohr's hypothesis.

On Bohr's theory there may exist at least three critical potentials in the range 10 to 17 volts, which if present would be quite difficult to accurately isolate and measure.

The hydrogen was generated electrolytically and streamed through hot copper, drying tubes and liquid air traps. Measurements by the Davis and Goucher method showed radiation without ionization near 10 volts, some ionization near 13 volts and

[5] *Proc. Roy. Soc. Lond.*, March, 1920.

[6] *J. Am. Chem. Soc.*, 37, p 457, 1915, 90,000 cal. per g. mol. at constant pressure.

strong ionization near 16 volts. Having shown that the 10-volt inelastic collision resulted in radiation without ionization, and that there were two ionization potentials, more accurate measurements were made by the methods employed with the other gases.

Partial current curves were obtained with two reversals, indicating successive resonance collisions. Often a pronounced break in the curves was occasioned by the second type of ionization. From these curves both the resonance potential and the second ionization potential may be obtained. The Lenard method showed both ionization points sharply. The following is a summary of our results:

Resonance potential = 10.4 volts.
First ionization potential = 13.3 volts.
Second ionization potential = 16.5 volts.

Without doubt the first ionization potential is for the atom and the second for the molecule. Hence the difference should give the energy required to dissociate hydrogen. This difference of 3.2 volts corresponds to a heat of dissociation per gram molecule at constant pressure of 74,000 calories, whereas Langmuir's observed value is 90,000 calories and the value derived from Bohr's theory of the molecule is 65,000 calories. The second ionization point may be observed with far greater precision than the first. Hence, if we assume the first point as 13.5 volts we obtain 16.5 – 13.5 = 3.0 volts, or 69,000 calories, in excellent agreement with the value computed from Bohr's theory of molecular hydrogen.

We have observed a slight evidence of a resonance collision between 2.5 and 3.5 volts, but have not been able as yet to secure curves with sufficiently pronounced inflections to permit the measurement of this voltage carefully. The work, however, indicates that hydrogen may be dissociated without ionization. This fact would not follow from the presence in the tube of monatomic hydrogen, as indicated by the resonance collisions, since the hydrogen is rapidly dissociated at the temperature at which the hot wire was operated. No doubt, even if hydrogen is dissociated without ionization by low voltage electronic impact, the greater part of the monatomic gas in the ionization tube is produced by the catalytic action of the heated filament.

The following table summarizes our data on the three gases:

Gas	Resonance potential		Ionization potential	
	Observed	Theoretical	Observed	Theoretical
Nitrogen	8.18	8.26	16.9	....
Oxygen	7.91	....	15.5	....
H_2	....	....	16.5	16.2
H	10.4	10.1	13.3	13.5

Dissociation of H_2

$16.5 - 13.3 = 3.2$ volts

$16.5 - 13.5 = 3.0$

Langmuir (experimental) $= 3.9$

Bohr (theoretical) $= 2.7$

BUREAU OF STANDARDS,
WASHINGTON, D. C.,
March 19, 1920.

1919 REPORT OF STANDARDS COMMITTEE ON VISUAL SENSITOMETRY.

BY

P. G. NUTTING, Chairman.

PRELIMINARY REPORT ON DATA.

VISION is accomplished through the influence of certain kinds of radiation upon the retina. The various responses of the retina to radiation correspond with those of a number of different kinds of physical instruments, each giving its particular kind of scale reading and each scale reading representing a certain sensibility or ratio of increment of scale reading to increment of stimulus producing it. The practical usefulness of our eyes is a matter of the sensibility and range of response of our retina to the stimulus of light in its various forms.

The quantitative study of the response of the retina to light practically began with the work of A. König twenty-five years ago. Subsequent advances in our knowledge of radiation made much more precise work possible and during the past fifteen years the investigation of the various responses of the retina to radiation has been vigorously prosecuted. At the present time, preliminary surveys of all the more important fields have been made, but much remains to be done in determining the properties of the average eye by observations on large numbers of subjects and in working out the numerous applications of this information to problems in photometry, illumination, colorimetry, etc., and to the design of optical instruments. This summary of our present knowledge of the subject covers: I. The Visibility of Radiation. II. Intensity and Contrast Sensibility. III. Chromatic Sensibility. IV. Rates of Adaptation. V. Absolute Sensibility.

I. THE VISIBILITY OF RADIATION.

The amount of radiant energy (measured in watts) necessary to produce a fixed luminous sensation of brightness (in lumens or lamberts), varies enormously with the wave length of the radiation. It is least in the mid-green, about .0015-watt lumen, at a wave length of about 556 millimicrons. The ratio is ten times as large in the blue-green on the one hand and in the red on

the other hand, and it is ten thousand times as large in the extreme violet (wave length 400) and extreme red (750). An eye well dark adapted perceives a light sensation from radiation at least as far out as 330 in the ultra-violet and 900 in the extreme red, if sufficiently intense.

Various methods have been employed by numerous observers in determining the relative visibility of radiation. A number of the earlier observers [1] measured the relative energies necessary to produce the threshold of light sensation. Another group [2] of observers used as a fixed standard of luminosity, that just sufficient to permit the correct reading of tables of numbers. König [3] used a white comparison field of fixed known brightness, that brightness varying in nine different sets of observations from the threshold of vision up to about 600-metre candles. Later observers [4] avoided the direct comparison of white with colored fields by using the flicker photometer for this purpose. Allen [5] obtains a visibility curve with no comparison field at all by simply noting the critical frequencies at which flicker just disappears at the various wave lengths. Hyde [6] has recently obtained excellent visibility curves by the step-by-step method, the brightness of each part of the spectrum being compared, not with a white standard but with a neighboring portion of the spectrum. The relative merits of these various methods have yet to be carefully investigated. There has been no lack of normal subjects; Ives had 19, Nutting 21, Hyde 29 and Coblentz and Emerson 125. The spectral energy of the acetylene flame, upon which most of the best data are based, is fairly well known, though several times revised. Improvements are to be looked for in the use of carefully studied sources, larger spectral apparatus of higher dispersion and a carefully chosen method of observation and of reduction of observations. All the modern data refer to visibility at moderate and high intensities (cone vision?). König's investigation of

[1] König and Dieterici, *Zs Psy. Sinnesorgans*, **4**, 241–347, 1893; A. Pflüger; *Ann. Physik.*, **9**, 185, 1902.

[2] S. P. Langley, *Am. Jour. Sci.*, **36**, 359, 1888.

[3] A. König, *Ges. Abh. Leipzig*, 1903.

[4] H. E. Ives, *Phil. Mag.*, **24**, 149, 1912; *Phys. Rev.*, **6**, 329, 1915; P. G. Nutting, *Trans. Ill. Eng. Soc.*, **9**, 633, 1914; Coblentz and Emerson, *Bull. Bu. Standards*, **14**, 167, 1918.

[5] F. Allen, *Phys. Rev.*, **9**, 257, 1900; *Phil. Mag.*, **38**, 85, 1919.

[6] E. P. Hyde, *Astroph. Jour.*, **48**, 87, 1918.

visibility at low intensities (rod vision?) should be repeated with modern apparatus and methods.

König's early data on relative visibility at various intensities, as reduced by the writer,[1] are given in the following table. There exists considerable uncertainty in these data due to uncertainties in (1) the correction for the dispersion in the prism employed and in (2) the spectral energy of the source (a gas flame). This latter determination was made for König by Langley in Washington on a somewhat similar gas flame.

König's Data on Visibility.

Intensities (m.c./mm² pupil) Ratio to preceding step	0.00024 (threshold)	.00225 9.38	.0360 16	.575 16	2.30 4	9.22 4	36.9 4	147.6 4	590.4 4
Wave length	Visibility								
430	0.081	0.093	0.127	0.128	0.114	0.114	....	....	....
450	.33	.30	.29	.31	.23	.175	.16	....	....
470	.63	.59	.54	.58	.51	.29	.26	.23	....
490	.96	(.89)	(.76)	(.89)	(.83)	.50	.45	.38	.35
505	1.00	1.00	1.00	1.00	.99	(.76)	.66	.61	.54
520	0.88	0.86	0.86	0.94	0.99	(.85)	0.85	0.85	0.82
535	.61	.62	.63	.72	.91	(.98)	.98	.99	.98
555	.26	.30	.34	.41	.62	.84	.93	.97	.98
575	.074	.102	.122	.168	(.39)	(.63)	(.76)	(.82)	(.84)
590	.025	.034	.054	.091	.27	.49	.61	.68	.69
605	0.008	0.012	0.024	0.056	0.173	0.35	(.45)	0.54	0.55
625	.004	.004	.011	.627	.098	.20	.27	.35	.35
650	.000	.000	.003	.007	.025	.060	.085	.122	.133
670	.000	.000	.001	.002	.007	.017	.025	.030	.030
Maximum....	.503	.504	.504	.508	.513	.530	.541	.543	.544

The shift of the visibility curve toward longer wave lengths with increasing intensities (the basis of the Purkinje effect) is clearly shown. The threshold visibility curve is reproduced in the accompanying figure.

In the following table are summarized the best data on the visibility of radiation of moderate and high intensities (cone vision). Absolute values of visibility or ratio of light to energy, in lumens per watt, are given in the final column. These are calculated from the visibilities on the basis of a mechanical equivalent of 0.0015 watt per lumen or a luminous equivalent of 667 lumens per watt for maximum visibility (at wave length 556).

[1] P. G. Nutting, *Bull. Bu. Standards*, 7, 235, 1910.

Data on Visibility.

(Ordinary Cone Vision.)

Wave lengths	Ives and Kingsbury	Nutting	Coblentz Emerson	Hyde, Cady, Forsythe	Adopted mean I. E. S.	Absolute visibility
400	0.0003	0.0021	0.006	0.00009	0.0004	0.27
10	.001	.0036	.011	.00062	.0012	0.80
20	.005	.0065	.015	.0041	.0040	2.7
30	.012	.0115	.020	.0115	.0116	7.72
40	.024	.022	.029	.022	.023	15.3
450	0.040	0.038	0.041	0.036	0.038	25.3
60	.060	.064	.058	.055	.060	40.0
70	.090	.101	.086	.087	.091	60.7
80	.137	.149	.128	.138	.139	92.6
90	.211	.215	.194	.216	.208	139
500	0.318	0.314	0.320	0.328	0.323	216
10	.473	.456	.503	.515	.484	322
20	.637	.646	.710	.698	.670	446
30	.801	.815	.862	.847	.836	557
40	.915	.925	.954	.968	.942	629
550	0.988	0.986	0.997	0.996	0.993	662
60	.996	.995	.998	.995	.996	663
70	.947	.949	.968	.944	.952	641
80	.859	.871	.898	.855	.870	580
90	.758	.762	.800	.735	.757	502
600	0.653	0.634	0.685	0.600	0.631	421
10	.534	.498	.555	.464	.503	336
20	.396	.368	.425	.341	.380	253
30	.283	.268	.305	.238	.262	175
40	.183	.166	.195	.154	.170	113
650	0.110	0.105	0.114	0.094	0.103	68.8
60	.068	.058	.062	.051	.059	39.3
70	.039	.032	.032	.026	.030	20.0
80	.026	.016	.0162	.0125	.016	10.7
90	.014	.0081	.0080	.0062	.0081	5.4
700	0.007	0.0036	0.0038	0.0031	0.0041	2.7
10	.....	.....	.00190	.0015	.0021	1.4
20	.....	.....	.00092	.00075	.0010	0.67
30	.....	.....	.00045	.00036	.00052	0.35
40	.....	.....	.00024	.00018	.00025	0.17
750	.....	.....	0.00015	0.00009	0.00012	0.08
60	.....	.....	.....	.00005	.00006	0.04
Wave length of maximum	556	556	557	556	556	

The visibility curve is roughly in the form of the well-known probability curve but slightly steeper on the violet side. It may be represented by the probability curve, but for mathematical

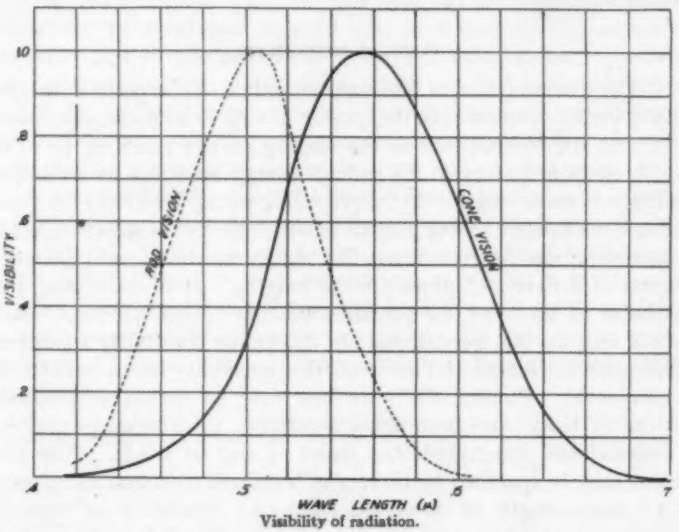
purposes (converting radiant energy into light), it is more convenient to use the form

$$V = V_m R^a e^{a(1-R)} \text{ or}$$
$$\log(V/V_m) = a(\log R + 1 - R)$$

in which $R = 556/\text{wave length}$, and $V_m = 667$ lumens/watt.

The absolute value of the visibility constant V_m in lumens per watt has been determined by a number of investigators. The

FIG. 1.



Visibility of radiation.

method used is to measure some convenient illumination both as light and as energy. The monochromatic green mercury line 546.1 has been used, also the nearly white light from an acetylene flame or incandescent lamp (integrated) and filtered white light. Even the best determinations are not in very good agreement, ranging from 625 to 667 lumens per watt. The corresponding value, the ratio of the lumen to the watt for rod vision, is yet to be determined.

A knowledge of the visibility of radiation, as determined by the reaction of the average normal fovea to radiation, is of the utmost importance in many branches of optics and illuminating engineering. The data given above are essential in reducing

radiant energy to light, for example, and in calculating the brightness of a heated body at a known temperature. It would be quite feasible to establish a standard of light in terms of radiant energy through similar data more accurately determined. In optical pyrometry and other problems it is necessary to calculate by means of the visibility curve the amount of light passed by a given light filter. It is to be hoped that the problems connected with the precise determination of visibilty may be attacked even more vigorously in the future.

II. COLOR SENSIBILITY.

The human retina is sensitive not only to differences in brightness, but to differences in the quality of that brightness, due essentially to the composition of the radiant energy reaching it. The differences in quality of the radiant energy are those of wave frequency or wave length. In the preceding paragraphs have been discussed the range of wave lengths to which the eye is sensitive; color discrimination depends upon the ability to distinguish between lights of different dominant wave lengths. It is, of course, impossible to set down the precise sensation corresponding to each wave length, but we can readily determine sensibility to differences in wave length and integrate this sensibility into a continuous color scale. Finally, the pure hue may be mixed with either white or black, and here again sensibility to differences may be observed and integrated into scales of tint or shade. Any one color may be specified by three and but three coördinates, namely (1) wave length of *dominant hue*, (2) *saturation* as regards admixture of white, and (3) *intensity* represented in the case of self-luminous bodies by emissivity and in other bodies by either reflecting or transmitting power for light.

Sensibility to differences in wave length may be readily determined by means of a modified simple spectometer having two collimators separately movable. While one is held fixed, the other is moved toward either longer or shorter wave lengths (usually each alternately), until the color difference is just noticeable. Then the movable one is held fixed while the other is loosened and moved to give a just noticeable difference in color. A good bright spectrum stepped off in this way gives from about 130 to 180 distinctly different pure hues between the red and violet, while from violet back to red through the purples and magentas there are about 20 additional steps as determined by their complemen-

taries in the green. The variation of color sensation with wave length is by no means uniform, as may be seen by a glance at a spectrum. In two regions, namely in the blue-green and in the yellow, hue changes very rapidly with wave length, while in the middle of the green and red, hue changes very slowly with wave length. Beside these two pronounced maxima of sensibility at wave lengths of about 490 (blue-green) and 585 (yellow), there are lesser maxima at about 637 in the red and 440 in the blue-violet.

The first reliable data of this nature were published by Steindler [8] in 1906 and reduced and published by the writer.[9] Steindler had 12 subjects, all with normal color vision. Curves were averaged not by taking the average sensibility at each wave length, but by finding the average wave lengths of each maximum and minimum of sensibility, since averaging the sensibilities would have given a mean curve flatter than any individual curve.

More recently this work has been repeated by Mr. L. A. Jones and the writer, using several forms of special spectrometer for the purpose. Our data are in very close agreement with those of Steindler taken 10 years previously in Vienna. Mr. Jones further made determinations [10] with his left eye as well as right eye, showing that the two eyes were practically the same in color sensibility. These data are summarized in the following table and figure:

Hue Sensibility.

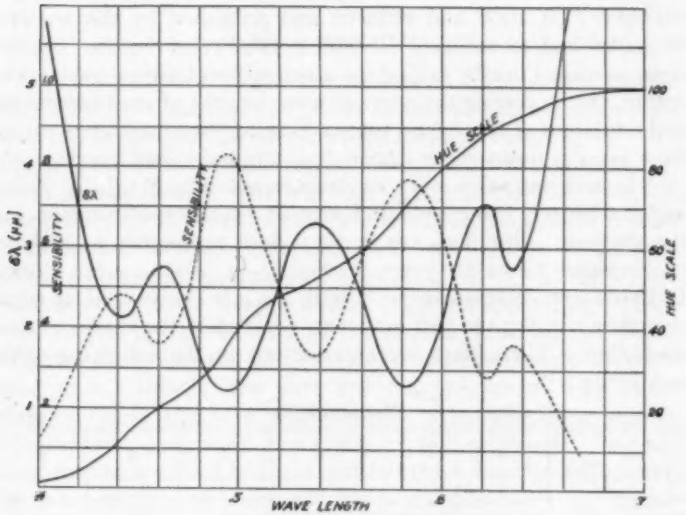
	A		*B*		*C*		*D*		*E*		*F*	
	λ	dλ	λ	dλ	λ	dλ	λ	dλ	λ	dλ	λ	dλ
At λ=660.....	660	6.0	660	5.2	660	5.0	660	...	660	5.4	660	6.0
First minimum...	635	2.8	638	2.4	637	2.4	635	3.1	637	2.5	637	3.0
First maximum...	622	3.4	628	3.5	623	3.2	620	3.7	624	3.4	621	3.7
Second minimum..	584	1.4	585	1.2	586	1.1	584	1.4	585	1.2	580	1.4
Second maximum.	538	3.5	540	3.3	537	3.2	538	3.0	538	3.3	535	3.3
Third minimum...	496	1.2	490	1.1	495	1.1	496	1.0	494	1.1	492	1.3
Third maximum..	462	2.3	465	2.4	464	2.5	465	1.9	464	2.4	458	3.1
Fourth minimum..	442	1.8	443	1.8	445	1.8	454	1.5	443	1.8	440	2.4
At λ=410.....	410	4.0	410	4.6	410	4.0	410	5.0	410	4.2	440	5.5

Column *A*.....First determination with right eye (discontinuous)
Column *B*.....Second determination with right eye (discontinuous)
Column *C*.....Third determination with right eye (continuous)
Column *D*.....First determination with left eye (discontinuous)
Column *E*.....Mean values of *A*, *B* and *C*.
Column *F*.....Mean values from Steindler data (12 subjects)

[8] O. Steindler, *Sitz. Ak. Wiss. Wien*, 115, 2A, Jan., 1906.
[9] P. G. Nutting, *Bull. Bu. Standards*, 6, 89, 1909.
[10] L. A. Jones, *Jour. Opt. Soc. Am.*, 1, 63, 1917.

The hue sensibility is taken as the reciprocal of the just noticeable difference in wave length. The hue scale is the integral of the sensibility with a factor to reduce the total range to a convenient number of units, 100 in this case. The scale obtained by Jones[11] by stepping off equal hue differences through the spectrum differs scarcely perceptibly from the scale obtained by integration. His data are given in the table on page 63.

FIG. 2.



Hue limen, sensibility and scale.

The amount of white that may be mixed with a pure hue before it becomes noticeable has been determined by the writer and L. A. Jones. Data are given in the following table:

Per cent. White ...	0,	10,	20,	30,	40,	50,	60,	70,	80,	90,	100
Per cent. Hue	100,	90,	80,	70,	60,	50,	40,	30,	20,	10,	0
Impurity noticeable	4.7,	4.6,	4.5,	4.4,	4.2,	4.0,	3.7,	3.4,	3.0,	2.5,	2.1

These data apply to red, green and blue; other hues have not been investigated. They apply to all moderate and high intensities

[11] Jones, *loc. cit.*

Just Noticeable Hue Differences.

No.	λ	δλ	No.	λ	δλ	No.	λ	δλ
1	700.0	....	44	576.5	1.4	87	490.4	1.1
2	678.0	22.0	45	75.2	1.3	88	89.4	1.0
3	65.0	13.0	46	73.7	1.5	89	88.2	1.2
4	59.0	6.0	47	71.7	2.0	90	87.0	1.2
5	54.0	5.0	48	70.1	1.8	91	85.8	1.2
6	49.5	4.5	49	68.4	1.7	92	84.5	1.3
7	46.0	3.5	50	66.6	1.8	93	83.2	1.3
8	42.8	3.2	51	64.8	1.8	94	81.7	1.5
9	40.2	2.6	52	63.0	1.8	95	80.0	1.7
10	37.8	2.4	53	61.1	1.9	96	78.2	1.8
11	35.5	2.3	54	58.6	2.5	97	76.5	1.7
12	33.1	2.4	55	57.0	2.6	98	75.0	1.5
13	30.0	3.1	56	54.4	2.6	99	72.9	2.1
14	26.5	3.5	57	51.8	1.6	100	70.5	2.4
15	23.0	3.5	58	49.1	2.7	101	68.2	2.3
16	20.0	3.0	59	46.1	3.0	102	65.8	2.4
17	17.3	2.7	60	43.0	3.1	103	63.6	2.2
18	14.9	2.4	61	39.8	3.2	104	61.2	2.4
19	12.5	2.4	62	36.5	3.4	105	58.7	2.5
20	10.2	2.3	63	33.2	3.3	106	56.5	2.2
21	08.0	2.2	64	30.1	3.1	107	54.4	2.3
22	06.0	2.0	65	27.1	3.0	108	52.1	2.3
23	04.1	1.9	66	24.2	2.9	109	50.0	2.1
24	02.3	1.8	67	21.4	2.8	110	48.0	2.0
25	600.6	1.6	68	19.1	2.3	111	46.0	2.0
26	599.0	1.6	69	16.8	2.3	112	44.2	1.8
27	97.4	1.6	70	14.6	2.2	113	42.5	1.7
28	95.9	1.5	71	12.6	2.0	114	40.8	1.7
29	94.5	1.4	72	10.6	2.0	115	39.0	1.8
30	93.1	1.4	73	08.0	1.6	116	37.2	1.8
31	91.8	1.3	74	07.0	1.0	117	35.3	1.9
32	90.5	1.3	75	05.4	1.6	118	33.3	2.0
33	89.5	1.0	76	04.0	1.4	119	31.3	2.0
34	88.5	1.0	77	02.6	1.4	120	29.3	2.1
35	87.5	1.0	78	01.3	1.3	121	27.0	2.2
36	86.4	1.1	79	500.0	1.3	122	24.8	3.2
37	85.3	1.1	80	498.7	1.3	123	22.3	2.3
38	84.0	1.3	81	97.4	1.3	124	19.7	2.8
39	82.7	1.3	82	96.1	1.3	125	16.7	3.0
40	81.5	1.2	83	94.8	1.3	126	13.8	2.9
41	80.3	1.2	84	93.7	1.1	127	10.4	3.4
42	79.1	1.2	85	92.6	1.1	128	405.8	4.6
43	77.9	1.2	86	91.5	1.1	...	.....	...

(cone vision). Hue sensibility, previously discussed, is also independent of intensity over a wide range of moderate and high intensities.

Various color analyzers, properly called colorimeters, make analyses in terms of pure hue and saturation. The so-called monochromatic analyzers determine color in terms of wave lengths of dominant hue and per cent. impurity. Trichromatic analyzers determine colors as ratios of three primary hues, which, when mixed, will just match the known sample. On account of the difficulty of making absolute analyses, color comparators, sometimes improperly called colorimeters, are much used. These instruments merely serve to determine color matches between the unknown and some prepared standard of color. That standard may be a colored solution, a certain thickness of quartz between crossed nicols, or various mixtures of prepared pigments. One of the most extensive and most carefully prepared sets of comparison standards was prepared by Robert Ridgway of the Smithsonian Institution, gotten out by Hoen of Baltimore. Ridgway takes 36 spectral hues and purples and dilutes each with white in three steps and with black in three steps. Each primary hue is further diluted with gray and these in turn diluted with white and black. The whole set consists of 1113 colors differentiated from each other by about twice the least perceptible difference.

III. SENSIBILITY TO INTENSITY.

The eye operates normally under intensities ranging from about 10 lamberts (the brightness of white paper in full sunlight) down to about one millionth of a millilambert. An average brightness out of doors on a clear day is about 1 lambert, in interiors during the day about 10 ml, in interiors at night 0.1 ml, out of doors at night 0.001 ml. The adapted threshold of vision is about 0.0000007 ml. In operating over this enormous range of 20 billion to one, the eye far exceeds in range any other physical instrument. It is enabled to do this by automatically adjusting its sensibility to the brightness of the field viewed. The sensibility of the retina varies by a factor of about 10 million, while the brightness of the field viewed varies by a factor of approximately 10 billion. It is sometimes assumed that variation in size of pupil takes care of the widely varying range of intensity of field, but this is not the case, since the total range of pupillary diameters is but from about 2 mm to 7.5 mm, or in area from 3 mm^2 up to 30 $mm.^2$ a range of but 10 : 1.

It is of course impossible by direct measurement to determine

the relation between brightness sensation and intensity of the stimulus producing that sensation. There are, however, various indirect means of determining that relation. With the retina adapted to any given field brightness, there is a corresponding (1) least perceptible brightness (threshold), (2) a least perceptible contrast in brightness, either in juxtaposed fields or in alternating fields, and (3) an intensity just uncomfortably glaring. Determinations of each of these quantities have been made for normal vision throughout the whole range of operating brightnesses.

Threshold sensibility is determined by means of the visual sensitometer.[12] A large cardboard illuminated to various known brightnesses is used to sensitize the eye. In the centre of this field is a spot independently illuminated. After the eye is fully adapted, the light on the large sensitized field is suddenly switched off and the brightness of the spot adjusted so that it is barely visible at the first instant of switching off the light of the large field.

The data taken by means of this method are given in the following table:

Adaptation in Brightness Sensibility.

(All Values are in Millilamberts.)

Field brightness	Instantaneous Threshold	T/F	T_s/T	Log F	Log T
0.00000071	0.00000071	1.00	1.00	−6.15	−6.15
0.00000100	0.00000093	0.93	0.77	−6.00	−6.03
0.0000100	0.0000042	0.42	0.17	−5.00	−5.38
0.000100	0.000019	0.19	0.038	−4.00	−4.72
0.00100	0.000093	0.093	0.0077	−3.00	−4.06
0.0100	0.00039	0.039	0.0018	−2.00	−3.41
0.10	0.00175	0.017	0.00041	−1.00	−2.76
1.00	0.0082	0.0082	0.000087	0.00	−2.09
10.0	0.036	0.0036	0.000020	+1.00	−1.44
100.	0.191	0.0019	0.0000037	+2.00	−0.72
1,000.	2.140	0.0021	0.00000033	+3.00	+0.33
2,000.	3.980	0.0020	0.00000018	+3.30	+0.60

The data for white light is the mean of that taken by Blanchard, Reeves and myself; the three subjects agree with each other in absolute sensibility to within the uncertainty in a single set of readings. The curve is a straight line except at the ends and with a very slight dip in the region of ordinary brightnesses, indicating

[12] P. G. Nutting, *Trans. Ill. Eng. Soc.*, 11, 7, 1916.

that there the retina is a little more sensitive than normal. The bending off near the threshold is due to the test field being considerably smaller than the sensitizing field. The falling off from the linear relation at high intensities is due to failure of retinal adaptation at high intensities. If continued, the curve would cut the 45-deg. line at about 7.1 lamberts, indicating that that brightness is blinding. (See Fig. 4.)

Data of a similar nature have been obtained for the four colors blue, green, yellow and red by Blanchard.[13] His determinations, after correction for the Purkinje effect in the specification of intensities, coincide with the curve of threshold sensibility obtained for white light to within the error of determination.

Contrast Sensibility, König and Brodhun.

Wave length	0.670	0.605	0.575	0.505	0.470	0.430	White
Field Br.	Least perceptible contrast						
1,000,000	.....	.....	.....	.....	.....	.....	0.0358
500,000	.....	.....	.....	.....	.....	.....	0.0273
200,000	.....	0.0425	.....	.....	.....	.....	0.0267
100,000	.....	0.0241	0.0325	.....	.....	.....	0.0195
50,000	0.0210	0.0255	0.0260	.....	.....	.....	0.0173
20,000	0.0160	0.0183	0.0205	0.0195	.....	.....	0.0175
10,000	0.0156	0.0163	0.0179	0.0181	.....	.....	0.0176
5,000	0.0176	0.0158	0.0166	0.0160	.....	.....	0.0179
2,000	0.0165	0.0180	0.0180	0.0175	0.0180	.....	0.0181
1,000	0.0169	0.0198	0.0185	0.0184	0.0167	0.0178	0.0178
500	0.0202	0.0214	0.0180	0.0194	0.0184	0.0214	0.0192
200	0.0220	0.0225	0.0225	0.0220	0.0215	0.0245	0.0222
100	0.0292	0.0278	0.0269	0.0244	0.0225	0.0246	0.0298
50	0.0376	0.0378	0.0320	0.0252	0.0250	0.0272	0.0324
20	0.0445	0.0460	0.0383	0.0295	0.0320	0.0345	0.0395
10	0.0655	0.0610	0.0582	0.0362	0.0372	0.0396	0.0477
5	0.0918	0.103	0.0888	0.0488	0.0464	0.0494	0.0593
2	0.1710	0.167	0.136	0.0655	0.0715	0.0600	0.0939
1	0.258	0.212	0.170	0.0804	0.0881	0.0740	0.123
0.5	0.376	0.276	0.208	0.0910	0.096	0.0966	.....
0.2	.....	0.332	0.268	0.110	0.127	0.116	.....
0.10	.....	.....	0.396	0.133	0.138	0.137	.....
0.05	.....	.....	.....	0.183	0.185	0.154	.....
0.02	.....	.....	.....	0.251	0.209	0.223	.....
0.01	.....	.....	.....	0.271	0.289	0.249	.....
0.005	.....	.....	.....	0.325	0.300	0.312	.....
0.002	.....	.....	.....	.....	.....	0.369	.....
Threshold	0.060	0.0056	0.0029	0.00017	0.00012	0.00012	0.00072

Contrast Sensibility.—If two fields of view side by side differ in brightness, there exists a minimum difference in brightness

[13] Julian Blanchard, *Phys. Rev.*, **11**, 81, 1918.

which is just perceptible. The ratio of this brightness difference to the mean of the two fields is the well-known Fechner fraction which is a constant over a wide range of intensities.

We are indebted to König and Brodhun [14] for the first investigation of contrast sensibility. Their data on white light and six pure hues are given in the table on page 66. Their unit of intensity was roughly 0.0040 millilamberts. Intensities for the colored lights are given as fractions of high intensities all equal. If corrected for the Purkinje effect, the thresholds and all contrast ratios for all colors would be sensibly equal at each intensity.

These data may be fairly accurately represented by the function $P = P_m + (1 - P_m)(F/F_o)^{-n}$. The values of the exponent n in this equation are given in the following table for the six different wave lengths:

	F_o	n	$P_m^{1/n}$	$P_m^{1/n} : F_o$
670	0.060	0.584	0.000832	0014
605	0.0056	0.388	0.0000234	0042
575	0.0029	0.364	0.0000116	0040
505	0.00017	0.335	0.00000434	0025
470	0.00012	0.323	0.00000276	0023
430	0.00012	0.323	0.00000276	0023

These values of course are only measures of the Purkinje effect. If the contrast sensibilities had been reduced to equal brightness sensations, the values for the different hues would have been sensibly equal and equal to the value for white.

Similar data have been obtained by Blanchard [15] and the writer using the visual sensitometer as devised by the writer. Contrast strips of varying densities were fastened across the test spot and adaptation curves run for contrasts of 0, .39, .67, .87 and .97. Our data check those of König and Brodhun, provided their unit of intensity was 0.0040 ml.

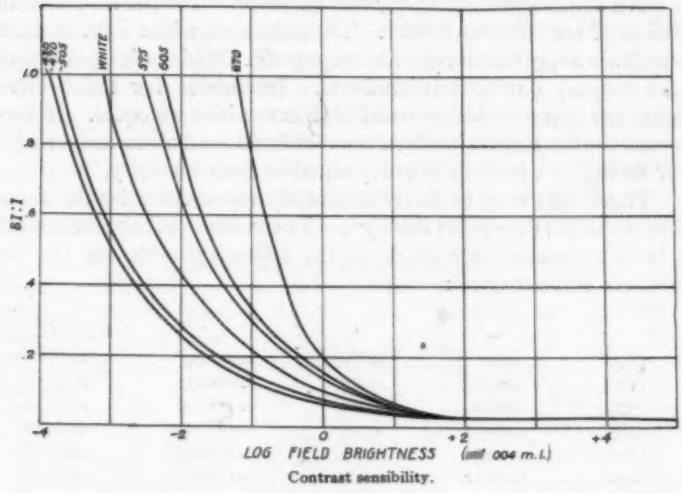
In the following table are summarized data on contrast sensibility over a wide range of field brightnesses. In the third column headed Discrimination Factor are plotted the reciprocals of the Fechner fraction, this being a measure of the relative ability of the eye to detect slight contrasts at the various intensities. The threshold limit is that previously given. In the fifth column are

[14] König and Brodhun, *Sitz. Ak. Berlin*, July 26, 1888; P. G. Nutting, *Bull. Bu. Standards*, 5, 285, 1908.

[15] P. G. Nutting, *loc. cit.*

given data obtained by multiplying the difference fractions by the field brightnesses. This quantity is the difference in millilam-

FIG. 3.



Contrast sensibility.

berts between the two fields which will appear just perceptibly different in brightness at each intensity. It is to be noted that this difference over a wide range of moderate intensities is just

Threshold, Contrast Difference and Glare at Various Field Intensities.

Field brightness	Difference fraction	Discrimination factor	Threshold limit	Difference	Glare limit
0.000001 ml	(1.00)	1.0	0.00000093 ml	0.0000010	20.1 ml
0.00001	(0.66)	1.5	0.0000042	.0000066	40.7
0.0001	0.395	2.5	0.000019	.0000395	89.
0.001 (E.N.)	0.204	4.5	0.000087	.000204	86.
0.01	0.078	12.8	0.00039	.00078	400.
0.1 (I.N.)	0.037	27.0	0.00174	.0037	810. ml.
1.0	0.0208	48.2	0.0081	.0208	1.66 l.
10. (I.D.)	0.0174	57.5	0.036	.174	3.47
100.	0.0172	58.1	0.28	1.72	7.25
1000. (E.D.)	0.0240	41.7	2.15	24.0	14.45
10000.	(0.048)	(20.9)	(232.)	480.	30.90

0.001 ml (E. N.) Exteriors at night, street lighting.
0.01 ml (I. N.) Interiors at night, interior artificial lighting.
1.0 ml (I. D.) Interior daylight lighting.
1.0 l. (E. D.) Exterior full daylight lighting.

twice the threshold limit to within the error in measurement. In other words, the difference in millilamberts between fields just noticeably different in contrast is twice the minimum perceptible brightness for an eye sensitized to the same mean field brightness. For example, with a mean field brightness of 0.1 ml, a rough average for interiors at night, the least perceptible difference is about 0.0037 ml, while the threshold limit is 0.00174 ml. The intensities indicated by initials in parenthesis are rough averages of those of most particular interest.

In Fig. 4 are plotted the logarithms of the just perceptible thresholds and contrast differences each in millilamberts for various brightnesses of field viewed. Both are linear functions of the field brightness and they are sensibly parallel. The mean slope of each line is two-thirds as closely as it can be read.

Taking sensibility as inversely proportional to these just perceptible intensities, we have therefore sensibility, $B :: F^{-2/3}$. The constant of proportionality is quite arbitrary. If it be taken such that sensibility is unity at the threshold, then we should have $B = (F/F_o)^{-2/3}$.

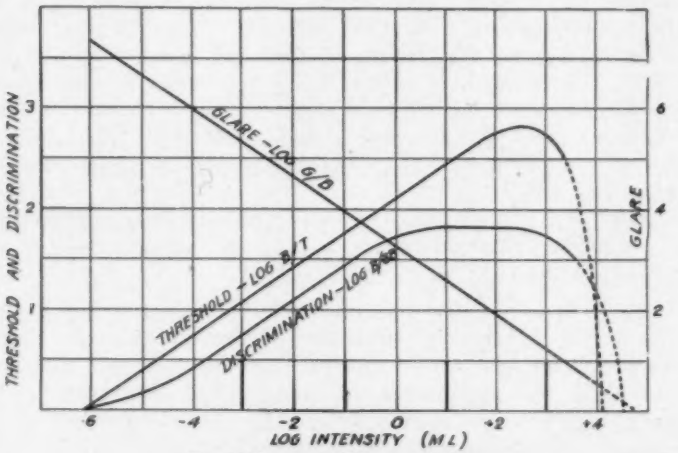
We are now in a position to determine the brightness sensation as a function of the stimulus by integrating the sensibility. This integral of BdF gives for the sensation, $S = 1/3\, F_o^{2/3}(F^{1/3} - F_o^{1/3})$. Hence we have that the sensation is proportional to the cube root of the brightness of the field viewed, except at the lowest intensities, the constant of integration being so chosen that the sensation becomes zero at the threshold. This cube root sensation law rests primarily upon the balance between the catabolic and metabolic processes in the visual purple. The energy flux per unit area at the retina is proportional to the brightness as defined and used in this paper.

Glare Sensibility.—In response to the need of automobile headlight engineers for data on brightnesses just intense enough to appear uncomfortable, determinations were made by the author, Mr. Blanchard, and Mr. Reeves.[16] The retina was sensitized to a definite field brightness, then a much brighter field suddenly flashed on. The three observers agreed surprisingly closely in their glare determinations, although these were made at different times and each observer formed his own criterion for judging glare. The mean results are given in the last column of the pre-

[16] P. G. Nutting, *loc. cit.*

ceding table and are plotted in Fig. 4. The logarithm of the glare is a linear function of the logarithm of the field brightness, the slope of the line being 0.32. From the slope and position of the glare line, brightness, $G = 1700F^{0.32}$. If the glare line be continued slightly, glare becomes equal to the field, or adaptation ceases at a field brightness of about 52 lamberts, five times as bright as white paper in direct sunlight. At night out of doors an average brightness is .001 ml and with the eye adapted to this average brightness, a field of 186 ml will just appear uncomfortably bright if suddenly flashed in the centre of vision.

FIG. 4.



Threshold, contrast difference and glare.

It is remarkable that both sensation and glare are proportional to the cube root of the brightness of the field viewed. This is less remarkable when we consider that the glare limit is a direct measure of the brightness sensation. From the last two equations it follows that if the unit of sensation is such that sensibility is unity and sensation zero at the threshold, then the glare limit is precisely 13 million times the sensation at each field brightness.

IV. RATE OF ADAPTATION.

If the eye is adapted to one mean brightness of field of view, that is to say, a given flux density of energy into the retina, then

the mean brightness of that field abruptly increased or diminished to another general level, the retina adapts itself to the new level of brightness at a given rate. The bulk of the adaptation takes place in the first few seconds, but in extreme cases continues at a gradually decreasing rate for many hours.

The visual sensitometer previously mentioned was devised by the writer primarily to study the rate of adaptation from one level to another. With this instrument a wide variety of adaptations may be studied very rapidly, since intensities are varied by sliding along a black wedge whose density is quite accurately proportional to the distance from the thin end. Our observations thus far have been chiefly on rate of adaptation from light to darkness, using various initial brightnesses, contrasts and colors, but the instrument is equally well adapted for determining adaptation from darkness to light. An earlier set of observations indicates quite clearly the general character and range of the phenomena involved. In this the eye was sensitized to a mean brightness of 25 ml, then this light suddenly switched off and the rate of increase in sensibility determined. Then the eye was fully adapted to darkness and suddenly exposed to a field brightness of 25 ml and the rate of sensibility decrease determined. These rough results are given in the following table:

Rates of Increase and Decrease of Sensibility.

Time	$B_0=0$, $B=25$ ml. Sensibility decrease	$B_0=25$ml., $B=0$ Increase
1 second	2.1 times	1.6 times
2 seconds	4.2 times	2.6 times
5 seconds	16.2 times	7.6 times
10 seconds	58. times	14.4 times
10 minutes	120. times	20.9 times

For example, if an eye adapted to darkness be suddenly exposed to 25 ml, its sensibility drops to 1/16 in 5 seconds, and a subsequent rest of 10 seconds will by no means restore its sensibility. An alternation of equal exposures to a light field will therefore produce a decided depression in sensibility. The application of such data in practise is obviously of importance as, for instance, in passing along an ordinary lighted street at night.

FIG. 5.

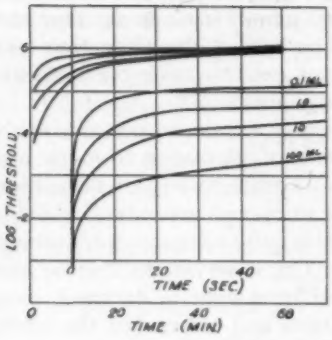
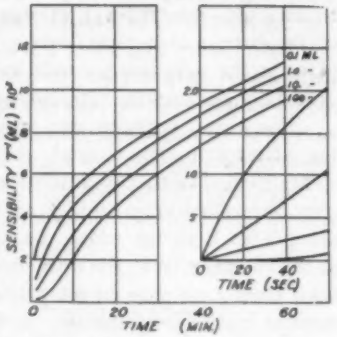
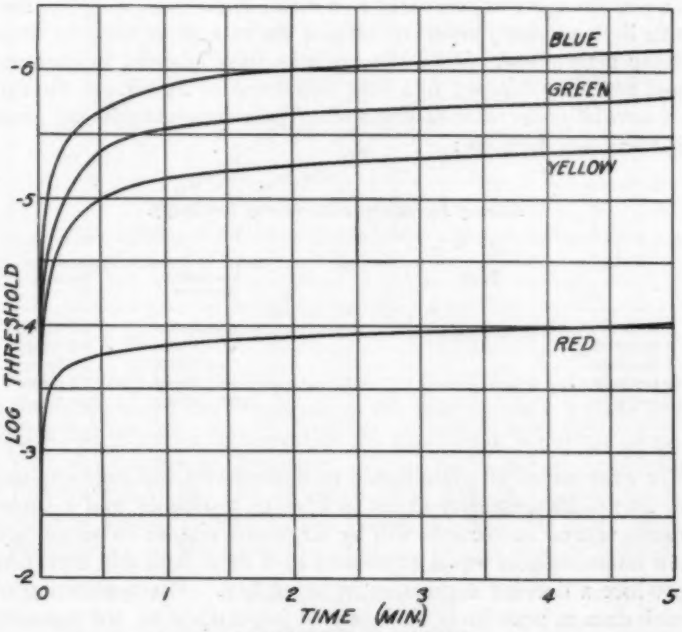


FIG. 6.



FIGS. 5 and 6.—Dark adaptation, white light.

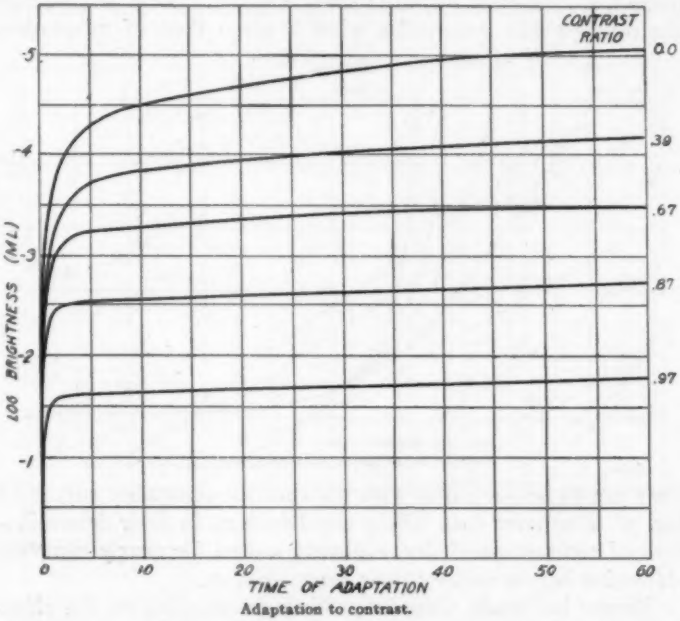
FIG. 7.



Dark adaptation, colored light.

The general phenomena of dark adaptation [17] are indicated in Figs. 5 and 6. The initial steady states from which adaptation proceeded were 0.1, 1.0, 10 and 100 ml. Curves are shown for each initial brightness, one set magnified in time to show the initial stages. These curves are not purely logarithmic as might have been anticipated. The sensibility taken as reciprocal of the just perceptible brightness of test spot is roughly proportional

FIG. 8.



Adaptation to contrast.

to the time of adaptation. This is shown in Fig. 6. When the pre-adaptation field brightness is small, the initial rise of sensibility is considerably greater than when the initial field is bright.

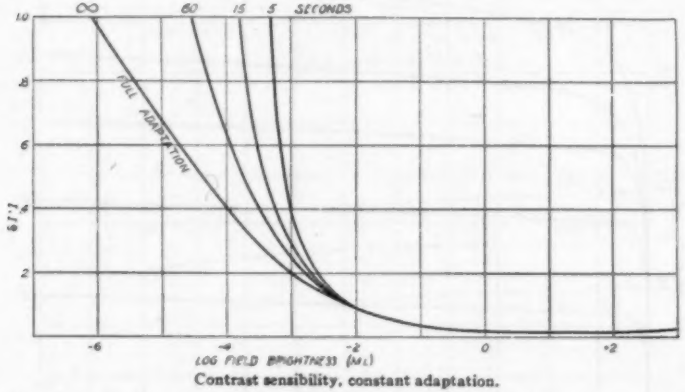
The rate of adaptation varies considerably with the color of the light used, as shown in Fig. 7 for the colors red, yellow, green and blue. The adaptation to red light is more rapid but does not proceed as far as that for blue light. Green and yellow give intermediate rates of adaptation. The rate for white of the same initial intensity lies between those for yellow and for green.

[17] P. G. Nutting, *loc. cit.*

Other determinations were made of the time necessary to just detect certain fixed contrasts: 0, .39, .67, .86 and .97. The results obtained are shown in Fig. 8.

These data were obtained by fixing across the test spot, strips of film whose transmission coefficients had the above values. Adaptation to slight (0.97 : 1) contrast is rapid but reaches nearly its final value in less than two seconds. Greater contrasts require longer and proceed farther in their adaptation. The same data plotted in a different way are shown in Fig. 9. These curves show the contrast just perceptible after a given time of adaptation.

FIG. 9.



Contrast sensibility, constant adaptation.

They are to be compared with the contrast sensibility curves of Fig. 3. From our data König and Brodhun, in their determinations of contrast sensibility, evidently waited for nearly complete adaptation before making their determination.

Reeves has made some interesting observations on the effect of size of test spot on contrast sensibility. The contrast used was 0.67. The test spots were square of the size indicated in the table below. These were viewed from a distance of 25 cm. The data are given in logarithms of brightness in ml.

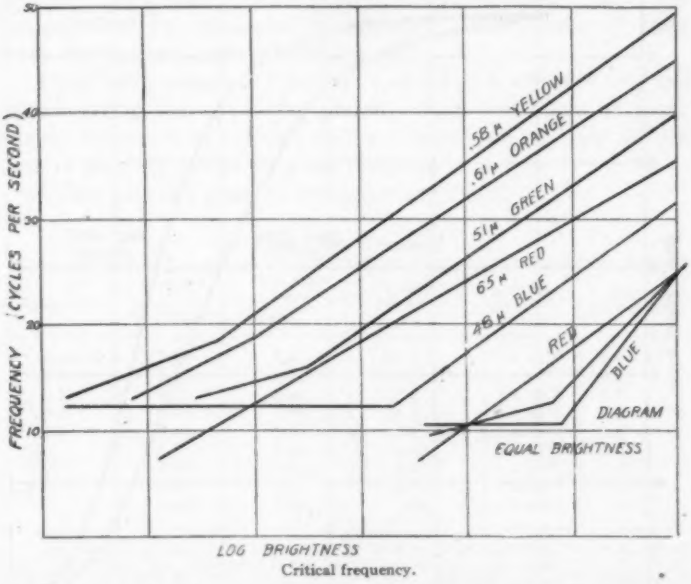
Effect of Size of Test Spot on Contrast Sensibility, Contrast 0.67.

Adaptation	3 cm. sq.	2.5 cm. sq.	1.5 cm. sq.	0.7 cm.sq.	0.3 cm. sq.	0.2 cm. sq.
0 second.....	−2.42	−2.10	−1.90	−1.69	−1.49	−1.31
2 seconds.....	−3.03	−2.64	−2.30	−1.91	−1.76	−1.46
10 seconds.....	−3.25	−2.93	−2.49	−2.11	−1.87	−1.58
60 seconds.....	−3.52	−3.25	−2.69	−2.27	−1.97	−1.69

It may be noted that the eye is nearly 100 times as sensitive for the 3 cm sq. test spot as for the 2 mm sq. test spot. This corresponds to the well-known fact, namely that signboards which are to be read quickly at night must be printed in large letters with heavy contrasts to be easily legible.

Critical Frequency.—The frequency at which flicker just disappears depends upon alternate light and dark adaptation of short period. Critical frequency is quite simply related to the brightness of the field viewed and has been used quite extensively as a

FIG. 10.



Critical frequency.

method for research in visual sensitometry. Porter [18] found that for white light the critical frequency at moderate and high field brightnesses is a linear function of the logarithm of the field

$$N_1 = 12.4 \log F + 24.9$$
$$N_2 = 1.56 \log F + 19.6$$

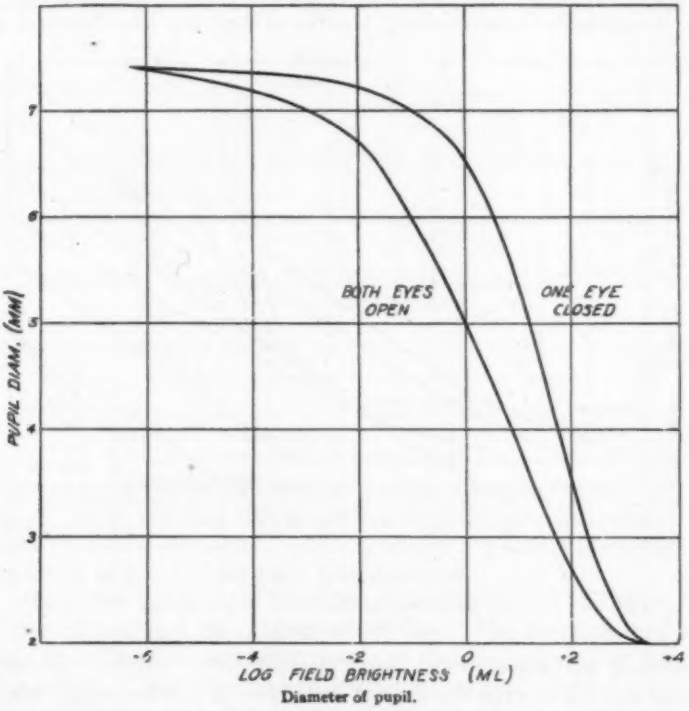
The second relation holds at low intensities down to the threshold. The field brightnesses are here given in meter candles. The

[18] T. C. Porter, *Proc. Roy. Soc.*, 70, 313, 1902.

logarithms are common logarithms and the frequencies are alterations per second of equal light and dark exposures. As a means of measuring illumination, however, the critical frequency is rather insensitive.

Similar work has been done by Ives [19] for various monochromatic pure hues. The relation between critical frequency and field brightness is linear throughout for red light. For blue light,

FIG. 11.



Diameter of pupil.

critical frequency is independent of brightness for all intermediate and low brightnesses. For other colors the relations are intermediate between these two extremes. Allen [20] has used a critical frequency method with great success in the investigation of afterimages in relation to the color vision theory.

[19] H. E. Ives, *Phil. Mag.*, Sept., 1912.

[20] Frank Allen, *Phil. Mag.*, July, 1919.

V. ABSOLUTE SENSIBILITY.

Diameter of Pupil.—All the data in the preceding sections of this paper were obtained with the normal pupil, with the exception of those on critical frequency for which a light in lumens or watts per sq. mm at the retina is directly proportional to the area of the pupil as well as to the brightness of the object viewed. All visual sensitometry involves the relation between size of pupil and mean brightness and angular size of object viewed.

Various pupilometers have been suggested and used for determining the size of pupil, but it remained for Blanchard and Reeves [21] to actually make precise determinations. This was accomplished by flashlight photography. The results of their work are shown graphically in Fig. 11.

Data were obtained for both eyes opened and for one eye closed during the sensitizing period. At a brightness of 1 ml, having the other eye closed makes a difference of fully 30 per cent. in the diameter of the pupil observed.

Other data are given in the following table:

Retinal Flux Densities.

Field, *Ml.* *F*	Observed (Diameter of pupil)	Effective (Diameter of pupil)	Area effective *S*	Lumens per mm² *E*	Lumens per mm²/ml.
0.00001	7.30	8.17	52.2	7.0×10^{-12}	7.0×10^{-7}
0.001	6.97	7.80	47.8	6.4×10^{-10}	6.4
0.01	6.65	7.44	43.4	5.8×10^{-9}	5.8
0.1	6.00	6.72	35.4	4.7×10^{-8}	4.7
1.0	5.06	5.66	25.1	3.3×10^{-7}	3.3
10.	3.86	4.32	14.6	1.9×10^{-6}	1.9
100.	2.72	3.04	7.25	9.7×10^{-6}	.97
1,000.	2.08	2.32	4.23	5.6×10^{-6}	.56
	2.00	2.24	3.94	1.1×10^{-4}	.11

(In the final column of this table are given the lumens per sq. mm. at the retina per ml. of field brightness. The calculations in the 5th column are based on the equation $L=(1/\pi) \times 10^{-6} FS\pi^2/\rho^2$, in which L is in lumens per sq. mm., F is field brightness in ml, S is the area of the effective pupil, π the mean refractive index of the eye media (taken as 1.34), and ρ is the equivalent back focal length of the eye (taken as 20.7 mm). The reduction factor of 1.14/1.02 was used to reduce from the observed apparent diameter of pupil to the actual entrance pupil of the system.)

Minimum Perceptible Radiation.—Reeves [22] has recently published some interesting data on the minimum energy necessary to excite the sensation of light. This is not a matter of light intensity alone, but involves both angular area of object

[21] Frank Allen, *loc. cit.*

[22] Prentice Reeves, *Astroph. Jour.*, April, 1919.

(area of retina exposed) and the time of exposure. His data on the relation between threshold and angular area are given in the following table:

Variation of Absolute Threshold of the Retina with Size and Shape of Stimulus.

Stimulus	Log. threshold	Threshold	Energy entering Eye
		Mi	*Ergs. per sec.*
1—mm. star at 3 m.....	−2.14267	0.00720	17.1×10^{-10}
1—mm. star at 1.5 m.....	−2.58503	.00260	24.8×10^{-10}
1—mm. star at 35 cm.....	−3.61979	.00024	42.1×10^{-10}
2—mm. square at 35 cm.....	−4.54837	0.000028	25.3×10^{-10}
5—mm. square at 35 cm.....	−5.17881	66	37.
1—cm. square at 35 cm.....	−5.61744	24	54.
2—cm. square at 35 cm.....	−5.99012	102	91.
3—cm. square at 35 cm.....	−6.34659	450	90.7
6—cm. square at 35 cm.....	−6.58872	258	208.
12—cm. square at 35 cm.....	−6.75647	175	564.

The energy entering the eye was calculated from the formula SFM^2/R^2 ergs per second in which S is the area of the test spot in cm², F its brightness in lamberts, M the mechanical equivalent of light; here taken as 1.59 ergs per second per cm², r the radius of the pupil, R the distance of the eye from the stimulus, in cm. As the mechanical equivalent of light has never been determined with any precision at these low intensities, the value used (1.59) may be subject to a very considerable correction factor.

Variation of Absolute Threshold of the Retina with Time of Exposure to Stimulus.

Time	Log. threshold	Threshold	1/T	T x Time
0.002	−3.44092	0.00036230	2.76	0.0672
.006	−4.01092	9752	10.3	58
.011	−4.35	4458	22.4	50
.020	−4.62	2394	41.7	48
.034	−4.91	1228	81.5	42
.160	−5.15	706	142.	.05113
.250	−5.29	512	195.	13
.500	−5.45	345	282.	18
1.000	−5.58	00262	382.	26
2.000	−6.11	77	1300.	15
4.000	−6.20	63	1588	25

Time is an essential factor in determining sensibility at these low intensities, as though the light were integrated in some way to

produce the threshold effect, which is of course dependent upon the ultimate reactivity of the retina, just as the glare limit marks the minimum reactivity. The data in the above table were obtained by using a carefully calibrated focal plane shutter for determining the time of exposure necessary, the test spot being 3 cm^2 at a 35 cm distance. The approach to constancy in the energy density of the retina given in the final column is very interesting indeed.

If the time of exposure is very much decreased, similar effects have been noted even at moderate and high intensities. Blondel and Rey [23] found that the sensation was proportional to the energy entering the eye in the first fraction of a second of time of exposure. Much important work remains to be done in this entire field of research.

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[23] *Trans. Ill. Eng. Soc.* 7, 625–662, 1912.

FOURTH ANNUAL MEETING OF THE OPTICAL SOCIETY OF AMERICA.

The Fourth Annual Meeting of the Optical Society of America was held at Columbia University, New York City, February 26 and 27, 1920. This meeting was to have been held in St. Louis with the A.A.A.S. in December but was postponed on account of traffic conditions. About 50 members of the society were in attendance. The program was as follows:

THURSDAY MORNING AT 10:00.

G. W. MOFFITT, Research Dept., Eastman Kodak Co.,
1. The Importance of Nodal Points in Lens Testing.
2. A Method for Determining the Photographic Absorption of Lenses.

L. T. TROLAND, Harvard University,
The " All or None " Law in Visual Response.

PRENTICE REEVES, Research Dept., Eastman Kodak Co.,
The Response of the Average Pupil to Various Intensities of Light.

A. H. PFUND, Johns Hopkins University,
The Optical Properties of Paints. (Not read.)

A. H. TAYLOR, Bureau of Standards,
A New Reflectometer for the Measurement of Diffuse Reflection Factors of Objects Diffusely Illuminated.

E. D. TILLYER, Research Dept., American Optical Co.,
Observations on the Reflections from Foliage.

F. K. RICHTMYER, Cornell University,
The Relation of X-ray Phenomena to the Problems of Optics.

L. A. JONES, Research Dept., Eastman Kodak Co.,
1. A Graphic Method for Solving Problems in Tone Reproduction.
2. A Colorimeter Operating on the Subjective Principle.

CHARLES SHEARD, Research Dept., American Optical Co.,
Convergence Associated with the Act of Accommodation at the Reading Point. (Read by Mr. Tillyer.)

C. W. FREDERICK, Dept. of Lens Design, Eastman Kodak Co.,
A New Soft Focus Screen for Portrait Photography.

THURSDAY AFTERNOON AT 2:00.

Address of the Retiring President, DR. F. E. WRIGHT, Geophysical Laboratory.

Progress in Crystal Optics During the Past Century.

Presentation and Discussion of the Preliminary Reports of the Committee on Nomenclature and Standards,

1. Colorimetry, I. G. Priest.
2. Pyrometry, W. E. Forsythe.
3. Photographic Materials, L. A. Jones.
4. Lenses and Optical Instruments, C. W. Frederick.
5. Photometry and Illumination, P. G. Nutting.
6. Polarimetry (no report).
7. Spectacle Lenses, E. D. Tillyer.
8. Projection Apparatus, H. G. Gage (no report).
9. Optical Glass, G. W. Morey.
10. Wave Lengths, W. F. Meggers.

THURSDAY EVENING AT 6:30.

Annual Dinner of the Society followed by the Business Meeting of the Executive Council.

FRIDAY MORNING AT 10:00.

P. D. FOOTE and F. L. MOHLER, Bureau of Standards,
Determination of Planck's Constant *h* from Metallic Vapors.

W. F. MEGGERS and P. D. FOOTE, Bureau of Standards,
A New Microphotometer for Photographic Densities.

FRED E. WRIGHT, Geophysical Laboratory,
The Resolving Power of a Microscope Using Polarized Light.

P. G. NUTTING, Research Dept., Westinghouse Co.,
Dispersion Formulas and the Testing and Listing of Optical Glass.

I. G. PRIEST, K. S. GIBSON, and H. J. MCNICHOLAS, Bureau of Standards, The Munsell Color System.

I. G. PRIEST, Bureau of Standards,
The Applications of Rotary Dispersion to Colorimetry, Photometry and Pyrometry.

I. G. PRIEST and P. D. FOOTE, Bureau of Standards,
A New Study of the Leucoscope and Its Application to Pyrometry.

F. E. Ross, Research Dept., Eastman Kodak Co.,
A New Formula for Photographic Resolving Power.
H. KELLNER, Research Dept., Bausch & Lomb,
A Simple Spectrophotometer.

FRIDAY AFTERNOON.

The Society visited the Keuffel and Esser Works at Hoboken.

The reports of the sub-committees of the Committee on Nomenclature and Standards were mostly of a preliminary nature, since considerable work and discussion will be required before such reports can be put in final form for adoption by the society. It was felt, however, that on account of the importance of such reports and their general usefulness to all workers in applied optics their preparation should be no longer delayed. After perhaps two more annual reports from each sub-committee, it has been planned to publish them in full in the JOURNAL. The discussion of the preliminary reports as presented was very animated and profitable.

P. G. NUTTING,
Acting Secretary.